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Estimating potential economic savings of water utilities due to improvements on technical and allocative inefficiencies

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ABSTRACT

This research investigated both technical and allocative inefficiencies in water utilities, and its impact on production costs. Using the stochastic frontier analysis (SFA) primal system, the study delved into the Chilean water sector between 2010 and 2017. Results showed an average technical inefficiency (TI) of 0.507 and allocative inefficiency (AI) of −0.417, indicating an overemphasis on capital over operational expenditures. The economic consequences of TI and AI were approximately US$ 1297 million and US$ 237 million per annum, respectively. On an individual scale, the increase on production costs due to TI and AI were estimated at 0.390 US$/m^3, 0.471 US$/m^3 and 0.038 US$/m^3 for full private utilities, concessionary utilities and the public utility, respectively. The results of the study evidence the need for holistic efficiency assessments to avoid biased policymaking, illuminating the prevailing trend of favoring capital expenditures, and revealing potential economic benefits for consumers.

1. Introduction

Historically, public utilities have been the most common supplier of water services to people [1,2]. However, over past decades many countries have transitioned toward privatizing their water services [3–5]. For instance, in England and Wales the water industry was fully privatized in 1989 and price cap regulation was employed to protect customers from the monopolistic nature of the industry. Similarly, in Chile the transition to a privatized water sector spanned from 1998 to 2004, resulting in the emergence of two distinct categories of entities: Full Private Utilities (FPUs) and Concessionary Utilities (CUs). While FPUs are characterized by private shareholders who both own and manage the infrastructure, CUs are essentially private entities that operate the infrastructure for a predefined tenure, based on a concessionary agreement [6]. In addition to the aforementioned cases, numerous European nations such as France, Spain, and Portugal, as well as some Latin American countries, have advocated for a partial integration of private entities into their water service provision. This has predominantly manifested in the form of Public-Private Partnerships (PPPs). Here, while the managerial functions are typically entrusted to private entities, the infrastructure predominantly remains publicly owned [4,5,7].

The driving forces behind these privatization endeavors predominantly to enhance the efficiency of water utilities, tap into external financing avenues for infrastructural advancements, and bolster environmental outcomes, particularly in areas concerning the quality of drinking water and wastewater treatment [8]. Consequently, numerous studies have undertaken evaluations of the efficiency of both public and private water utilities, as chronicled in comprehensive literature reviews by Cetrulo et al. [9] and Goh and See Ref. [10]. Despite these extensive examinations, a consensus regarding the superior efficiency of a particular ownership model—public or private—has remained elusive [11]. Further complicating matters is the predominant focus of much of this research, which often fails to distinguish between different categories of private water utilities, like FPUs and CUs [6,12,13]. The exploration of the distinct efficiency dynamics of FPUs and CUs has been largely limited as it does not exist in many countries worldwide. To fill this gap in literature, our study focuses on the Chilean water industry

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where full private, concessionary and public water utilities exist. Through this focused lens, our study aims to offer insights and shed light on the distinct efficiencies and operational modalities of these diverse ownership structures.

Certain notable studies have ventured to compare the performance of FPUs and CUs, providing varied insights into their efficiency dynamics. Molinos-Senante and Sala-Garrido [6] and Sala-Garrido et al. [2] leveraged non-parametric techniques to gauge the technical efficiency (TE) and productivity shifts of multiple Chilean water utilities. Alternatively, Molinos-Senante et al. [14,15] tackled a similar analysis, but opted for parametric techniques. The insights derived from these studies present a nuanced picture. On one hand, research by Molinos-Senante and Sala-Garrido [6] and Molinos-Senante et al. [14] suggested superior performance by FPUs in comparison to CUs. Conversely, Sala-Garrido et al. [2] and Molinos-Senante et al. [15] concluded that CUs outperformed FPUs. Thus, the findings are inconclusive, revealing divergent performance trends. Adding another dimension to this analysis, a recent investigation by Molinos-Senante and Maziotis [16] discovered that the sole PU operating in Chile demonstrated higher TE than its private counterparts.

While the aforementioned studies compared the performance of FPUs and CUs in Chile offer pioneering insights, they do come with certain limitations. Firstly, except for the research by Molinos-Senante and Maziotis [16], the studies largely overlooked the performance of any PU in Chile, focusing primarily on FPUs and CUs. Secondly, the focus of the past studies remained confined to estimating only TE, sidelining allocative efficiency. The distinction is essential. While technical inefficiency (TI) points to a utility's inability to minimize inputs for a given output, allocative inefficiency (AI) deals with a company's failure to optimally distribute its resources in the light of its input prices [17]. Given that cost efficiency encompasses both these efficiencies, it becomes imperative to estimate both. Merely being technically efficient does not guarantee cost efficiency if allocative inefficiencies are rife, and conversely. Thus, for a holistic understanding, these inefficiencies should be evaluated collectively. Failing to do so might result in biased efficiency estimations [18]. Thirdly, previous research largely neglected investigating how the inefficiencies of water utilities impact their production costs. Understanding this is essential as it translates to tangible financial implications and can influence both operational strategies and regulatory frameworks.

This study fills this gap in literature by jointly estimating the TI and AI of FPUs, CUs and PU in the Chilean water industry. The study further extrapolates the implications of these inefficiencies, discerning their tangible impact on the production costs specific to each utility type. This deeper exploration provides a comprehensive understanding of the financial ramifications of inefficiencies within the Chilean water industry. By doing so, we aim to offer a more holistic perspective, shedding light on the interplay between operational inefficiencies and their consequent cost implications, thereby enriching the discourse on water utility performance.

Our study contributes to the current strand of literature as follows. First, we use an innovative approach to jointly estimate the TI and AI in the water industry. Thus, a company may operate well in terms of TE but an over or under use of inputs (AI) may lead to overall cost inefficiencies. Moreover, we explore how TI and AI affect the demand for inputs as it can provide more information on how a company could reduce its production costs. Furthermore, this technique allows us to quantify the impact of TI and AI on the costs of production. Finally, we add more evidence on the efficiency and ownership nexus of the water industry.

2. Methodology

The methodological approach employed in this study embraces five main stages as it is shown in Fig. 1.

2.1. Estimation of technical and allocative inefficiencies

The inefficiency of water utilities, both technical and allocative, is estimated using the stochastic frontier analysis (SFA) primal system method introduced by Kumbhakar and Wang [18]. This method leverages the production function and the primary conditions for cost minimization to concurrently assess the TI and AI of water utilities. Additionally, this approach enables the distinct quantification of production cost increments resulting from these inefficiencies [19]. The use of the SFA concept allows us to include the effect of TI and AI in the production practice. Furthermore, since both TI and AI may increase production costs, the SFA primal approach allows us to estimate the increase in the production cost that is associated with each type of inefficiency [20]. Nevertheless, it is important to highlight that a significant limitation of SFA is its dependence on stringent parametric specifications for both the estimation of the frontier and the conditional density of the regressand of interest [21]. To address this constraint, as a first step, a Cobb-Douglas production function is determined in conjunction with the first order conditions for cost minimization (FOCs). The Cobb-Douglas production function represents the relationship between inputs and the output of a production process (provision of

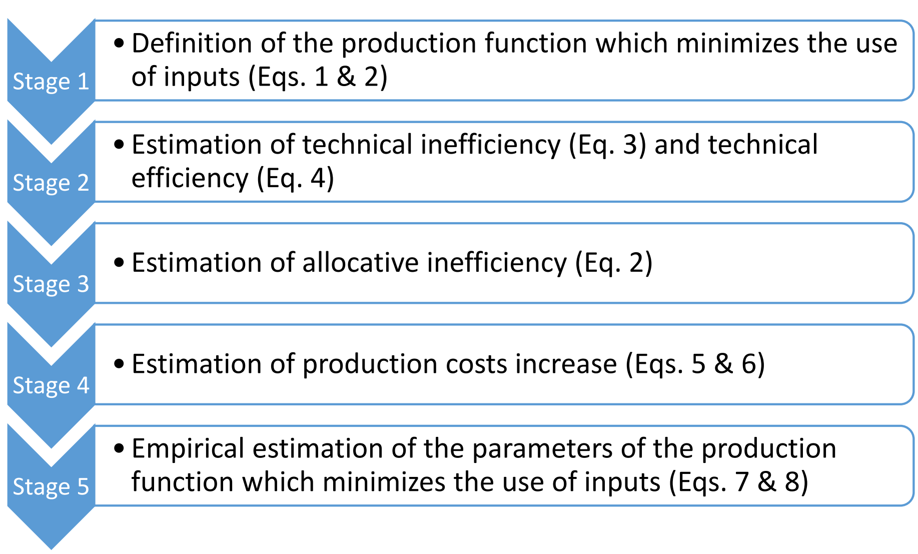

Fig. 1. Main methodological stages of the study.

drinking water in this study). Moreover, in the context of cost minimization, the FOCs are used to determine the input mix that minimized the total cost of production while still producing a given level of output.

The selection of Cobb-Douglas is due to the small sample size, which means fewer degrees of freedom are needed [22]. The Cobb-Douglas production function and the FOCs are defined in Eqs (1) and (2), respectively:

$$lny = \beta_0 + \sum_j \beta_j lnx_j + \sum_j \gamma_j lnz_j + \nu - u = f(x) + \nu - u \quad (1)$$

$$\frac{f_j}{f_1} = \frac{w_j}{w_1} e^{\xi_j} \Rightarrow \frac{\frac{\vartheta lnf}{\vartheta lnx_j}}{\frac{\vartheta lnf}{\vartheta lnx_1}} \equiv \frac{s_j}{s_1} = \frac{w_j x_j}{w_1 x_1} e^{\xi_j}, \quad (2)$$
$$\Rightarrow lns_j - lns_1 - ln(w_j x_j) + ln(w_1 x_1) = \xi_j$$

In Eq. (1) y denotes the output generated, i.e., volume of water supplied, by the use of several inputs, i.e., operating and capital expenditure ($j = 2$), z denotes the set of environmental variables, i.e., percentage of water leakage and the number of water unplanned supply interruptions ($j = 2$), ν is the noise term which follows the normal distribution, $\nu \sim N(0, \sigma_\nu^2)$ and u is assumed to follow the half-normal distribution, $u \sim N(0, \sigma_u^2)$ [18].

In Eq. (2), f presents the first derivative of the production function with respect to the set of inputs, w_j presents the price of input j; s_j denotes the cost share of input j and ξ_j is the AI for the input pair $(j, 1)$ where x_1 is the numeraire and ξ_j is independent of the error term and the inefficiency terms (ν and u) and is distributed with a non-zero mean as $\xi_j \sim MVN(\rho, \Sigma)$ [18].

Based on Eqs. (1) and (2), TI of each water utility is calculated based on Jondrow et al. [23]'s approach and subsequent development [24–26]:

$$TI(u|(\nu - u)) = \mu^* + \sigma^* \frac{\phi\left(\frac{\mu^*}{\sigma^*}\right)}{\Phi\left(\frac{\mu^*}{\sigma^*}\right)} \quad (3)$$

where ϕ denotes the standard normal density function and Φ is the standard normal cumulative distribution function, $\mu^* = -(\nu - u)\sigma_u^2 / \sigma^2$ and $\sigma^* = \sigma_u \sigma_\nu / \sigma$ [19].

Subsequently, based on Eq. (3), the TE of each water utility is computed as follows:

$$TE = \exp(-u) \quad (4)$$

TE scores range from zero to one. A water utility with a score of one is deemed to be fully technically efficient, while scores less than one signify TI.

The AI for the input pair (x_j, x_1), denoted as ξ_j, is derived from Eq. (2) [27]. The sign (either positive or negative) of the AI indicates whether there is an underuse or overuse of input x_j relative to the numeraire inputs such as x_1[19]. For instance, if $\xi_2 > 0 \Rightarrow w_2 e^{\xi_2} > w_2$ then input x_2 is underused relative to input x_1. The AI is then expressed as per percentages of overuse and underuse of the input factors, i.e., is $100 \times (e^{\xi_2} - 1)$ *per cent* [19,28].

2.2. Estimation of production costs increase

By estimating both AI and TI, it becomes possible to calculate the increase in production costs for water utilities due to these inefficiencies as detailed below.

To assess the influence of TI and AI in the production process, Eqs. (1) and (2) are utilized [20]. This involves employing the input demand functions for x_j and x_1, respectively:

$$lnx_j = \delta_j + \frac{1}{\tau}\sum_{j=1}^{J} \beta_i lnw_i - lnw_j + \frac{1}{\tau} lny + \frac{1}{\tau}\sum_{i=2}^{J} \beta_i \xi_i - \xi_i - \frac{1}{\tau}(\nu - u), \quad (5)$$
$$j = 2$$

$$lnx_1 = \delta_1 + \frac{1}{\tau}\sum_{j=1}^{J} \beta_i lnw_i - lnw_1 + \frac{1}{\tau} lny + \frac{1}{\tau}\sum_{i=2}^{J} \beta_i \xi_i - \frac{1}{\tau}(\nu - u) \quad (6)$$

where $\tau = \sum_i^J \beta_i$ denotes returns to scale and $\delta_j = lna_j - \frac{1}{\tau}\left[\beta_0 + \sum_i^J \beta_i ln\, \beta_i + \sum_j \gamma_j\, ln\, z_j\right]$.

Eqs. (5) and (6) evidence that all error components (TI, AI and noise), returns to scale and price of inputs affect input demand function [18]. Regarding the effects of inefficiency on inputs, TI causes a rise in the use of all inputs by $\left(\frac{1}{\tau} u_{i,t}\right)$ 100 percent [28]. AI, being unconstrained, can either augment or reduce input usage [29]. Nonetheless, the presence of AI invariably results in increased production costs.

In line with the input demand x_j, we derived the input demand for x_j when only TI exists, x_{jTI} and the input demand for x_j when only AI exists, x_{jAI} [18]. Then we multiply the price of each input with the input demands x_{jTI} *and* x_{jAI} to compute the corresponding costs c_{TI} and c_{AI} [20]. Thus, we derive the increase in cost due to TI and allocative AI, c_{tech} and c_{alloc}.

2.3. Empirical estimation of parameters

Given that our study incorporates data from multiple water utilities, denoted as n, over a time period, t, the model depicted in Eq. (1) is represented as follows [18,20,27]:

$$lny_{nt} = \beta_0 + \sum_j \beta_j lnx_{jnt} + \sum_j \gamma_j z_{jnt} + \beta_t t + \nu_{nt} - u_{nt} = f(x) + \nu_{nt} - u_{nt} \quad (7)$$

Thus, the FOCs are defined as follows:

$$lns_{jnt} - lns_{1nt} - ln(w_{jnt} x_{jnt}) + ln(w_{1nt} x_{1nt}) = \xi_{jnt} \quad (8)$$

The parameters of the models presented in Eqs (7) and (8) are estimated by maximizing the concentrated log-likelihood function [19]. Additionally, from the estimation of the model parameters, both returns to scale (RTS) and technical change (TC) can also deduced. The calculation for RTS is given as follows:

$$RTS_{nt} = \sum_j \frac{\vartheta lny_{nt}}{\vartheta lnx_{jnt}} = \sum_j \beta_j \quad (9)$$

If $RTS_{nt} > 1$, then decreasing returns to scale are present, indicating that a 1 % increase in outputs might lead to an increase of more than 1 % in costs. Conversely, if $RTS_{nt} < 1$, it denotes the existence of increasing returns to scale. Meanwhile, a value of $RTS_{nt} = 1$ signifies constant returns to scale [30].

Moreover, TC was derived as follows:

$$TC_{nt} = \frac{\vartheta lny_{nt}}{\vartheta t} = \beta_t \quad (10)$$

A positive value of TC, i.e., $TC_{nt} > 0$, means technical progress over time, whereas if $TC_{mt} < 0$, then technical regress may be present.

3. Case study

3.1. Urban water industry in Chile

Our study focuses on 20 water utilities operating in Chile from 2010 to 2017. The privatization of the Chilean water industry started on 1998 and, after the completion of the privatization process in 2004, two types of private water utilities formed, FPUs, CUs [6]. A small proportion of customers, 3.5 %, is also served by a public water utility (PU) [31]. Within the scope of our analysis, we examine 11 FPUs, 8 CUs, and a singular PU. Together, they serve an estimated 90 % of Chile's urban population.

Regardless of ownership, all Chilean water companies operate under a uniform regulatory framework. This framework is founded on the principles of the General Law of Sanitary Services, established in 1988, and the General Law of Tariffs in Sanitary Services, implemented in 1989. The economic regulatory model used to set water tariffs in Chile is the "model-firm" approach, also known as the "efficient water company model." According to this model, water tariffs are determined on the assumption that water companies operate with technical and economic efficiency, as defined by the regulator's "model" or efficient water company standard [32].

Every five years, the following procedure is implemented for each water company: The regulator, Superintendencia de Servicios Sanitarios (SISS), drafts terms of reference for the water tariff studies to be conducted by both the water company and the SISS. The findings from each study are shared between the two parties, leading to negotiations on water tariffs. If a consensus is reached, the tariffs are established through a decree signed by the Minister of Economy and ratified by the Nation's Comptroller. Should no agreement be reached, an expert committee reviews both studies and sets the final water tariff. The decision of the expert committee is final and not subject to appeal by any party. The water tariff determined by the expert committee is formalized in the final water tariff decree (Molinos-Senante and Donoso, 2026).

Within this regulatory framework, the objectives of the water tariffs applied in Chile are to: i) Finance the operating costs, maintenance, and investment requirements of water companies to ensure the continuity of water supply and quality service; ii) Finance a minimum agreed operational margin that covers the companies' capital opportunity cost; iii) Incentivize efficiency gains in the provision of water services; iv) Pass on efficiency gains to customers through tariff reductions; v) Provide water value signals so that consumers internalize the scarcity value of water in their region [33].

3.2. Data and sample selection

According to past research assessing the technical and economic efficiency of water utilities [9,10,34,35], the volume of drinking water delivered, measured in thousands of cubic metres per year, is selected as output in the production frontier model. Moreover, the quality of the drinking water plays a significant role in influencing the operational costs of water utilities (Chan et al., 2022; [36]). To integrate the varying water quality provided by each water utility over the years into our analysis, the delivered volume of water is adjusted using a drinking water quality index, which is annually estimated by the Chilean regulator. It is a synthetic index ranging between 0 and 1. A score of 1 indicates that the water utility consistently meets all established water quality standards. Consequently, when the water quality index falls below 1, the resultant output in our model, termed as the quality-adjusted volume of water delivered, will invariably be less than the actual volume of water delivered [31].

In terms of inputs and their associated prices, we utilize two primary inputs. The first input is the annual operating expenditure (Opex), quantified in Chilean pesos on a yearly basis. Its corresponding price is inferred using the Chilean producer price index, as sourced from national statistical data [37–39]. The second input pertains to the annual capital expenditure (Capex), which represents financial outlays aimed at network enhancement, and is also evaluated in Chilean pesos per year. The capital's price is ascertained by determining the quotient of capital expenditure and the monetary worth of tangible assets, as described by Coelli et al. [17] and Molinos-Senante et al. [39]. Both Opex and Capex are adjusted for inflation using the consumer price index, also derived from national statistics. For the purpose of our analysis, the Opex and its respective price served as the benchmark or numeraire input and input price.

Since 2010, Chile has been grappling with a severe, prolonged drought [40]. Given this backdrop, potential environmental factors that could impact the performance of utilities are identified and considered. Specifically, we incorporate two environmental variables into our evaluation: i) water leakage, defined as the percentage of produced drinking water that goes unaccounted for, i.e., it is produced but it is not delivered to end-users [14] and; ii) the duration of unplanned water supply interruptions for which the water utility is responsible. This is gauged in terms of hours per annum, shedding light on service reliability [41].

The data source for our study is the Chilean urban water regulator, known as Superintendencia de Servicios Sanitarios (SISS), and is procured from their official website. Table 1 depicts the descriptive statistics for the variables employed in this study.

4. Results and discussion

4.1. Estimation of technical inefficiency and allocative inefficiency

The results from the estimation of the production frontier model are reported in Table 2. All the variables except for the variable time were statistically significant from zero. Technically speaking, a 1 % increase in the quality-adjusted volume of water supplied might increase operating inputs and capital by 0.754 % and 0.179 %, respectively. The more water is delivered to the customers the lower the percentage of water leakage and unplanned interruptions as indicated by the negative sign of these variables. This finding implies a good quality of service. Technical change had a negative sign indicating technical regress at a small rate of 0.06 % per year but this finding was statistically insignificant. The estimated parameter σ_u^2 was statistically significant from zero which means that the use of stochastic production frontier is justified [20]. Moreover, the RTS of the Chilean water industry was estimated at 1.003 indicating that the industry operates under constant returns to scale.

From the estimated production function (Table 2), the TI and AI of each Chilean water utility were calculated. Key statistics for both parameters are depicted in Fig. 2. The average TI for Chilean water utilities stood at 0.507. This indicates that, on average, the utilities produced 50.7 % below their maximal potential output due to technical inefficiencies, as interpreted from Kumbhakar and Wang [18]. To put it differently, in accordance with Eq. (4), the mean TE of the Chilean water utilities was approximately 60.2 %. This implies that, on average, the utilities have the potential to reduce their inputs, water leakages, and unplanned water interruptions by nearly 39.8 %%, all while maintaining their existing output level. Regarding AI, the mean input AI for Capex was found to be negative, suggesting an overuse of Capex in comparison to Opex. As illustrated in Fig. 2, the average AI was at −0.417. This denotes that Capex was overutilized by 41.7 % relative to Opex.

The trend in the TE and AI for each type of water utility according to its ownership are shown in Fig. 3. The mean TE scores for FPUs, CUs, and the PU stood at 0.685, 0.557, and 0.866, respectively. This indicates that the PU outperformed its private counterparts in terms of TE. However, given that only one PU operates within Chile, these results warrant a prudent interpretation. Generally, from 2010 to 2014, TE remained almost constant for all water utilities, irrespective of their ownership type. However, this trajectory was noticeably interrupted during the 2014–2016 period. This observation aligns with the findings of prior studies conducted by Sala-Garrido et al. [2] and Maziotis et al. [41]. In these studies, both teams documented a dip in the performance metrics of Chilean water utilities when service quality determinants, such as water leakage and interruptions in water supply, were incorporated into the analysis. The authors noted that this might have been attributed to the extreme hydro meteorological events and earthquakes, which impacted the water supply networks [41].

Focusing on AI, average values for FPUs, CUs and the PU are −0.441,

Table 1
Descriptive variables of the water utilities evaluated.

Variables	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Quality adjusted volume of water delivered	000 s m^3/year	53,688	94,386	895	457,567
Operating expenditure	000s CLP/year	34,488,931	42,875,279	799,873	201,122,273
Capital expenditure	000s CLP/year	16,545,261	29,673,021	136,197	216,596,205
Price for opex	Index	90.51	7.03	80.40	100.00
Price for capex	Index	0.07	0.05	0.01	0.28
Water leakage	%	32.45	10.04	9.30	51.20
Water supply unplanned interruptions	hour/year	4946.80	7454.92	2.50	34050.90

Observations: 160.
Costs and input prices are expressed in 2017 prices.

Table 2
Estimated production frontier parameters.[a]

Variables	Parameter	Coef.	Std. Err.	z-sta	P > z
Constant	β_0	15.432	1.233	**12.520**	0.000
Opex	β_1	0.754	0.161	**4.683**	0.000
Capital	β_2	0.179	0.036	**4.927**	0.000
Time	β_t	−0.006	0.012	−0.500	0.618
% of water leakage	γ_1	−0.272	0.107	**−2.540**	0.011
Water unplanned supply interruptions	γ_2	−0.197	0.033	**−6.050**	0.000
	σ_u^2	−0.895	0.230	**−3.900**	0.000
	σ_u^2	−0.493	0.143	**−3.453**	0.000
Log likelihood	−263				
observations	160				

Bold estimates are statistically significant at 95 % confidence level.
[a] Quality-adjusted volume of water delivered is the dependent variable.

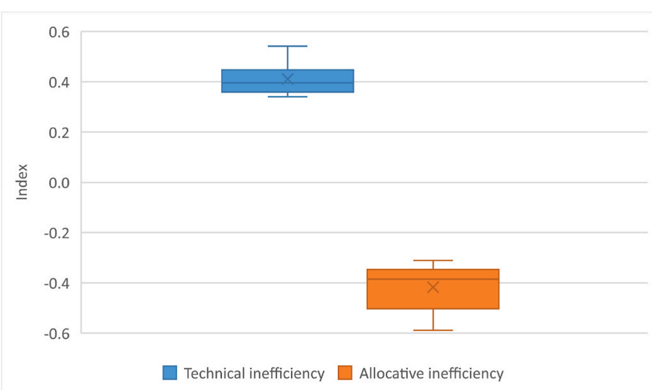

Fig. 2. Statistics of technical inefficiency and allocative inefficiency in the Chilean water sector.

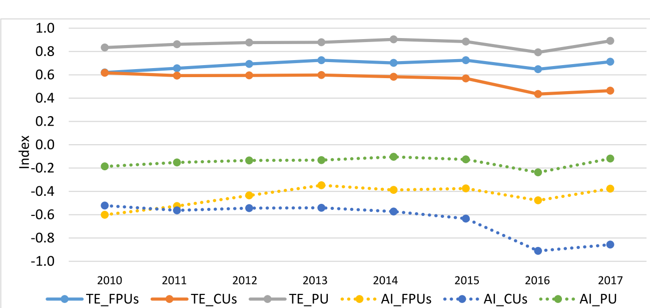

Fig. 3. Evolution of technical efficiency (TE) and allocative inefficiency (AI) of Chilean full private utilities (FPUs), concessionary utilities (CUs) and public utility (PU).

−0.643 and −0.149, respectively. This indicates that all three types of water utilities in Chile exhibit a propensity to overutilize Capex in comparison to Opex, with this trend being most pronounced in CUs and least in the PU. In particular, the overuse of Capex is estimated to be 44.1 %, 64.3 % and 14.9 % for FPUs, CUs and PU, respectively. Various factors could underpin this observed pattern, with the raw water source emerging as a potential explanatory element. Notably, a majority of CUs extract raw water from groundwater sources, while FPUs utilize a mix of resources - predominantly surface water but supplemented with groundwater. In terms of temporal progression, AI displays distinct patterns based on the utility's ownership. For the PU and FPUs, AI largely remained steady throughout the evaluated period, with a minor uptick (in absolute values) witnessed in 2016 – this correlates with the observed TE scores. Conversely, starting from 2014, CUs began to show a marked rise in their average AI (in absolute values), peaking at −0.911 in 2016. This translates to a significant 91.1 % overutilization of Capex relative to Opex.

When examining both performance indices, namely TE and AI, it becomes apparent that the PU demonstrates the best performance, exhibiting the highest TE and the lowest AI. Conversely, CUs display the least favorable performance metrics, characterized by minimal technical and allocative efficiency. The three distinct types of water utilities in Chile—FPUs, CUs and PU— operate under an identical regulatory framework. Hence, variations in TE (Fig. 3) and AI (Fig. 4) are not attributable to regulatory differences. Instead, discrepancies in performance among these utilities may stem from managerial influences, as Molinos-Senante and Farias [42] observed that CUs tend to prioritize short-term economic goals over technological advancements. Additionally, external factors such as demographic and geographic conditions, along with the incidence of natural disasters, may also impact the TE and AI metrics, thereby justifying the observed differences among the water companies.

The findings on AI revealed that water utilities in Chile tend to overuse Capex in relation to Opex. This inclination can be attributed to the broader regulatory framework of the urban water sector and, more specifically, the tariff-setting procedure. Although the cost recovery

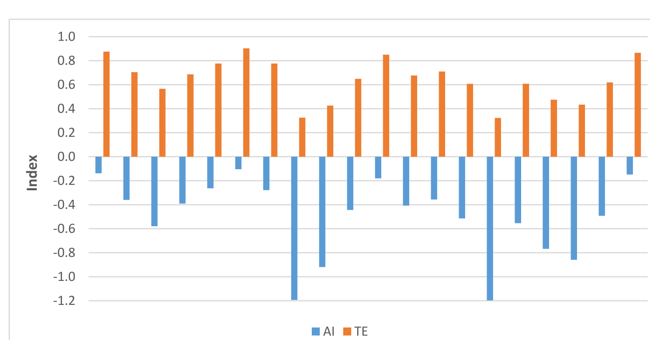

Fig. 4. Average allocative inefficiency (AI) and technical efficiency (TE) of Chilean full private utilities (FPUs), concessionary utilities (CUs) and public utility (PU) from 2010 to 2017.

principle incorporates both Opex and Capex into water tariffs, there's a distinctive regulatory requirement for water utilities. Every five years, water utilities are mandated to formulate a "development plan" that meticulously outlines the necessary investments envisaged to guarantee consistent water supply in the forthcoming years [31]. Given this regulatory landscape, water utilities find it more straightforward to increase the use of Capex, rather than the recurrent day-to-day operational costs associated with facility management. This regulatory and planning bias, thus, provides an explanation for the observed preference towards Capex over Opex.

Reducing the overuse of Capex over Opex by Chilean water utilities requires implementing various measures and policies by both water companies and the regulator (SISS). Key strategies, based on current practices in Chile, include improving knowledge of the physical state of infrastructure, which is currently limited for both utilities and the regulator. Water companies should develop comprehensive plans to monitor asset performance and anticipate maintenance needs, enabling a shift towards prioritizing operational interventions rather than costly infrastructure replacements. The adoption of digital tools in managing the urban water cycle in Chilean cities remains minimal. Incorporating technologies such as sensors and Internet of Things (IoT) devices for leak detection, real-time water quality monitoring, and consumption measurement could significantly reduce the need for large-scale infrastructure upgrades. Given that water leakage rates have remained constant over the past 15 years [31], advanced leakage detection methods are urgently needed to minimize water loss. From a management perspective, it is essential to base water regulation on lifecycle analysis to evaluate total costs. This approach would ensure that investments are directed towards solutions that prioritize long-term sustainability over capital-intensive, short-term fixes.Average results from TE and AI at a utility level are shown on Fig. 4. The TE showed considerable variability among Chilean water utilities, with average TE scores ranging from as low as 0.323 (for CU4) to as high as 0.903 (for FPU6). This substantial range underscores the diverse performance levels among these utilities. The top-performing utility, FPU6, is of medium size, supplying approximately 35,000,000 m^3 of the best quality drinking water annually. This is substantiated by its consistent quality index of 1.000 across all evaluated years, indicating that it consistently meets all established water quality standards. On the flip side, CU4, which exhibited the lowest TE, is a smaller utility, distributing around 5,000,000 m^3 of water annually. Notably, CU4 also recorded the lowest average drinking water quality index over the period from 2010 to 2017, with a score of 0.920. These observations emphasize the significance of incorporating the quality-adjusted volume of water when assessing the efficiency of water utilities. It demonstrates that performance is not solely about quantity, but also about the quality of the delivered water.

In terms of AI, two utilities, FPU8 and CU4, stand out due to their pronounced AI values, registering at −1.193 and −1.197 respectively. This indicates that these two utilities exhibit the most significant overuse of Capex relative to Opex. Notably, both these utilities display water leakages that are below the national industry average for Chile. For the period from 2010 to 2017, FPU8 and CU4 had average water leakages of 13.48 % and 26.19 %, respectively. In comparison, the industry-wide average for Chilean water utilities during this period was 32.45 %. Conversely, FPU6 and the PU recorded the lowest AI values, marked at −0.104 and −0.149, respectively. However, when examining leakage percentages, both these utilities reported considerably high values, with FPU6 and PU recording 38.75 % and 43.14 % respectively. This data implies a correlation where limited Opex used in pipeline maintenance results in higher leakage percentages. Furthermore, the lower AI values in these utilities suggest a more balanced allocation between Capex and Opex.

4.2. *Estimation of the impact of technical and allocative inefficiencies on production costs*

TI and AI of water companies involve an increase in their production costs, i.e., in the costs for the provision of drinking water. According to statistics for the Chilean water industry depicted in Fig. 5, the average surge in production costs attributable to technical inefficiencies was 43.5 %, while AI accounted for a 7.9 % increase. Considering that the annual average total expenditure of the Chilean water utilities evaluated was around 2,402,764 million CLP (≅ US$ 3002 million), production costs in Chile increased by US$ 1297 million/year and US$ 237 million/year due to TI and AI, respectively. In other words, if the evaluated Chilean water utilities operated at optimal technical and allocative efficiency levels, they could potentially achieve annual savings nearing US$ 1537 million.

The augmented production costs, attributable to TI and AI, varied from US$ 2914 million in 2012 to US$ 5602 million in 2017 (Fig. 6). This variation across the evaluated years can be ascribed to the specific TI and AI indices estimated for each year and the respective annual total expenditures of the water utilities. However, a consistent theme throughout the evaluation period (2010–2017) was the dominant role of TI in escalating the production costs of the scrutinized Chilean water utilities. Specifically, TI accounted for a substantial 90.1 % of the cost increase in 2012 and 77.4 % in 2013. From 2012 onwards, there's a discernible uptick in production costs, predominantly driven by declining TE. In light of these findings, to achieve cost reductions in water production and distribution, it becomes imperative for water utilities to address their TI. This can be achieved through optimizing input utilization and/or enhancing service quality.

In order to compare the performance of the three types of water utilities assessed - namely FPUs, CUs and the PU – an analysis was undertaken to determine the increase in production costs per cubic meter of delivered water over the period 2010–2017 (Fig. 7). Notable divergences among water utilities are observed since the minimum increase in production costs is 0.038 US$/$m^3$ for the PU and the maximum is 1.229 US$/$m^3$ for the FPU8. On average, FPUs could reduce its costs by 0.390 US$/$m^3$ if they were technically and allocatively efficient. For CUs, this potential reduction is larger, standing at 0.471 US$/$m^3$. By contrast, the PU has a comparatively modest potential savings, amounting to an average of 0.038 US$/$m^3$. The estimated increases in production costs are associated with TI and AI of water utilities (Fig. 4) but also with the annual volume of water delivered by each utility.

In general, FPUs deliver a larger volume of drinking water compared to CUs and the PUs, which consequently impacts their production costs per cubic meter of water. Nevertheless, an examination of the results at the water company level (Fig. 5) reveals substantial variations within each category of utilities, i.e., FPUs and CUs. Specifically, for FPUs, the increase in operational costs attributed to TI and AI ranges from US

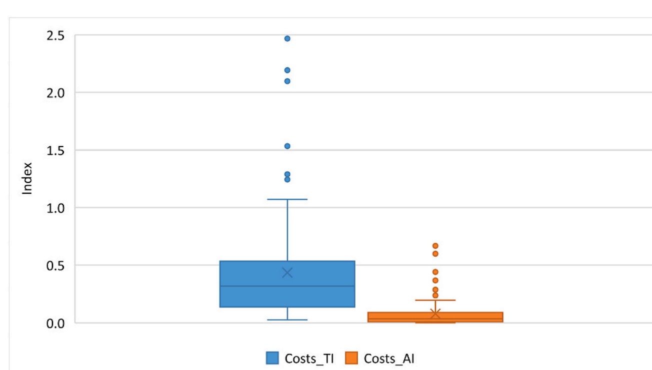

Fig. 5. Statistics of increase in production costs due to technical inefficiency (TI) and allocative inefficiency (AI) of the Chilean water utilities evaluated.

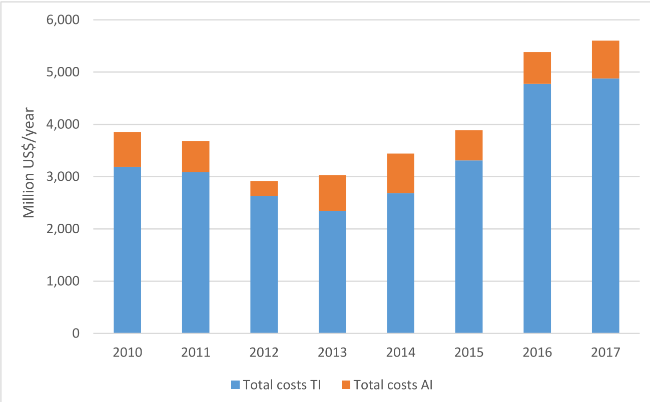

Fig. 6. Evolution of the increase in production costs due to technical inefficiency (TI) and allocative inefficiency (AI) of the Chilean water utilities evaluated.

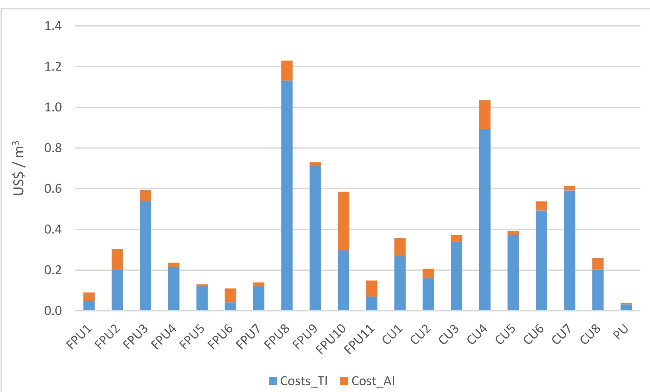

Fig. 7. Average increase in production costs for full private utilities (FPU), concessionary utilities (CU) and public utility (PU) due to technical inefficiency (TI) and allocative inefficiency (AI).

$0.090 to US$1.289 per cubic meter. Similarly, a significant range is also observed for CUs, with costs varying from US$0.206 to US$1.035 per cubic meter. These disparities suggest that differences in operational costs are not solely linked to the ownership structure of the utilities but are also significantly influenced by managerial strategies and external factors specific to each utility at the individual level.

The technical and allocative performance conducted in this study integrates water leakage and unplanned water supply interruptions as relevant variables. Hence, potential actions to be adopted by the water utilities to improve its efficiency should be go further than a reduction in the use of inputs. Some potential measures that water utilities could adopt to reduce TI and AI are as follows: i) use Opex to improve the maintenance of the infrastructure as it could improve utilities' energy efficiency, reduce operational costs, and also contribute to minimize water leakage; ii) develop asset management plants to reduce infrastructure investments based on condition assessments and medium- and long-term maintenance needs; iii) optimize water pumping and distribution to reduce energy use and water leakage; iv) develop and implement a master plan for disaster risk management, including risk reduction and resilience measures, to minimize unplanned water supply interruptions; v) implement new and improved water demand forecast models to make informed decisions about investment needs and; vi) explore the use of alternative water sources to reduce costs on water abstraction and treatment in a drought context as Chile faces. In this context, in 2023, approximately 21 % of the total wastewater volume generated in Chile was discharged into the sea, amounting to around 261 million cubic meters. This volume represents a significant opportunity for regeneration and reuse in various applications, including aquifer recharge. Moreover, the collection of fog water might be of great importance in coastal ecosystems in arid zones such as the North of Chile [43]. Preliminary studies have shown that in certain areas, the potential for fog water harvesting can reach up to 30,000 m^3 per year [44]. This represents an alternative water source that Chilean water utilities should consider exploring further.Some of these measures have been successfully implemented in various countries. For instance, in the United States, the American Water Works Association has developed an Excel-based tool to help determine the effective useful life of facility-based treatment, storage, and pumping assets for water utilities [45]. Regarding disaster risk management, Japanese water utilities have significantly advanced their capabilities to plan and execute risk mitigation and emergency response strategies [46]. In the context of water demand forecasting, deep learning and machine learning techniques have proven to be effective tools, already deployed in select cities in Korea and India [47].

The regulatory framework governing the Chilean urban water sector was established in 1988 (see Section 3), which means it does not address some contemporary issues such as climate change mitigation and adaptation, responsiveness to rapid demographic shifts, or resilience against natural hazards. This rigid framework limits the adoption of certain effective policies seen in other countries that enhance water sector performance. A noteworthy comparison is with the private water utilities in England and Wales, which continuously adapt policies to reduce TI and AI in the water industry. Here, the price review process, conducted every five years, defines dynamic mechanisms to encourage water companies to enhance their performance. For instance, the 2019 price review by the English and Welsh water regulator emphasized customer service, resilience, affordability, and innovation. This review introduced changes from the 2014 review to promote outcomes beneficial for customers and the environment, aligning with the sector's vision for the future [48]. In contrast, the 2024 price review focuses on long-term goals, driving improvements through efficiency and innovation [49]. This flexible regulatory approach allows the regulator to adopt specific policies to boost efficiency. Unlike in Chile, where legal amendments are often necessary to implement new policies, creating political and ideological obstacles that hinder the process.

The findings of this study, while rooted in the Chilean water sector, have significant implications for privatized water utilities worldwide. The challenges of TI and AI identified in this research are not unique to Chile. Similar inefficiency patterns have been observed in other privatized water sectors, such as those in England, Wales, and parts of Spain and France [50]. These parallels underscore the importance of regulatory frameworks that incentivize a balanced approach to expenditure. A key insight from this study is the potential for regulatory biases to influence expenditure patterns. This phenomenon is relevant in other privatized water systems, where tariff-setting mechanisms often emphasize capital investment to ensure long-term infrastructure reliability. Furthermore, this study's methodological approach—quantifying the economic impact of inefficiencies—provides a template for other nations to assess the potential economic savings achievable through improved utility performance. By integrating measures of both TI and AI, regulators in other regions could develop more holistic strategies to incentivize efficiency gains, ultimately reducing consumer costs. Finally, the findings stress the critical role of ownership and management structures in shaping performance outcomes. This observation echoes global debates on the relative merits of public versus private ownership in water service provision.

5. Conclusions

Traditionally, the assessment of water utilities performance has focused on measuring TE while often overlooking allocative efficiency. Nevertheless, a comprehensive evaluation of water utilities' performance should encompass both forms of efficiency. It is important to note that inefficiency, whether technical or allocative, results in increased production costs for water utilities. Quantifying this inefficiency is crucial in order to demonstrate the economic implications of reduced efficiency in the water utility sector.

In this study, we introduced a novel approach by employing the SFA primal system to concurrently assess both technical and allocative efficiency in the water services sector and to analyze their impact on production costs for water utilities. Our empirical investigation focused on the Chilean water industry, encompassing FPUs, CUs, and a PU during the period from 2010 to 2017. The key findings from our analysis can be summarized as follows: i) the average TI and AI for the Chilean water industry were 0.507 and −0.417, respectively. This suggests an excessive allocation of Capex compared to Opex. Ii) significant disparities were identified among different types of water utilities, with PU displaying the best performance. The PU had a TE score of 0.866 and an AI score of −0.149 in contrast with the CUs whose TE was 0.557 and AI was −0.643; iii) the average economic impact of TI and AI in the water industry was estimated to be US$ 1297 million per year and US$ 237 million per year, respectively and; iv) on a water utility level, the average increase in production costs for FPUs, CUs, and PUs was found to be 0.390 US$/$m^3$, 0.471 US$/m^3, and 0.038 US$/$m^3$, respectively.

The assessment conducted in this study holds significant implications for researchers and policymakers beyond its specific findings in the context of the Chilean water industry. There are several key reasons why this study is of great interest. Firstly, the study underscores the importance of evaluating water utilities' efficiency from both technical and allocative perspectives. Neglecting one aspect can result in an underestimation of inefficiencies, potentially leading to biased policy decisions regarding investment requirements for water utilities by regulatory bodies. Secondly, the estimation of AI reveals a prevalent practice of overemphasizing Capex over Opex within water utilities. This insight would not be apparent to water regulators if only TI is assessed in performance evaluations. Thirdly, the methodological approach employed in this study allows for the estimation of the economic impact of both TI and AI on water utilities. Given that many countries base water tariffs on the cost recovery principle, quantifying the production cost due to inefficiencies in water utilities serves as a proxy for potential economic savings for citizens in terms of lower water tariffs.

CRediT authorship contribution statement

Alexandros Maziotis: Writing – original draft, Software, Formal analysis, Conceptualization. **Ramon Sala-Garrido:** Writing – review & editing, Methodology, Data curation. **Manuel Mocholi-Arce:** Writing – review & editing, Resources, Formal analysis. **Maria Molinos-Senante:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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